A re-evaluation of the capabilities of the long-baseline super-beam neutrino experiments in the presence of a sterile neutrino

Debajyoti Dutta
Harish-Chandra Research Institute,
Allahabad-211019

In collaboration with
Raj Gandhi, Boris Kayser, Mehedi Masud, Suprabh Prakash

The impact of sterile neutrinos on CP measurements at long baselines

by Raj Gandhi, Boris Kayser, Mehedi Masud, Suprabh Prakash; JHEP 1511 (2015) 039; arXiv:1508.06275v2

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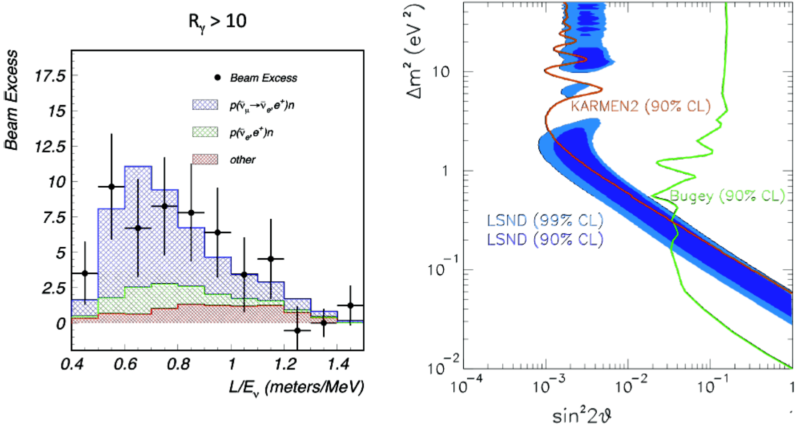
Open Questions

- CP violation in lepton sector?
- Absolute mass scale of neutrinos?
- Mass ordering: sign of Δm^2_{31}?
- Precision: $\theta_{23} > \pi/4, \theta_{23} < \pi/4, \theta_{23} = \pi/4$?
- Majorana vs Dirac?
- Sterile neutrino(s)?

Sterile Neutrino(s)

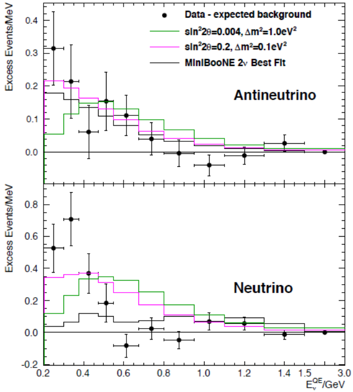
- Our thinking usually assumes the standard neutrino scenario, which contains just 3 neutrino mass eigenstates, and just 1 (oscillation-relevant) CP-violating phase
- But a variety of SBL anomalies hint at the existence of short-wavelength ($L/E \sim 1km/GeV$) oscillations, driven by splittings $\Delta m^2_{41} \sim 1eV^2$
- These large splittings imply additional neutrino mass eigenstates, beyond 3, that are largely sterile

Signature of sterile sector: SBL anomalies (LSND)



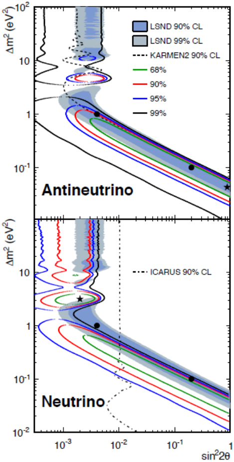
Phys. Rev. D 64, 112007

Signature of sterile sector: SBL anomalies (MiniBoone)



Antineutrino Event Excess from 200-1250 MeV = 78.4+-20.0+-20.3 (2.8σ)

Neutrino Event Excess from 200-1250 MeV = 162.0+-28.1+-38.7 (3.4σ)



PRL 110, 161801 (2013)

Motivation of our work

- Recent works suggest for possible existence of one or more neutrino in addition to the standard 3+0 scenario.
- Indication of small mixings with the 3 SM neutrinos with $\Delta m^2_{41} \sim 1ev^2$
- $\Delta m^2_{31} \sim 2.5 \times 10^{-3} ev^2$, $\Delta m^2_{21} \sim 7.5 \times 10^{-5} ev^2$, $\Delta m^2_{41} \sim 1ev^2$
- $\Delta_{ij} = 1.27 \times \frac{\Delta m^2_{ij}[\mathrm{eV}^2] \times L[km]}{E[GeV]}$
- $\Delta_{41} \sim \Delta_{42} \sim \Delta_{43} >> |\Delta_{31}| \sim |\Delta_{32}| >> \Delta_{21}$
- At L = 1300 km, the finite energy resolution of the far detector will average the rapid oscillations driven by the large $\Delta m^2_{41} \sim 1eV^2$ to an energy-independent, but nonzero, value
- Two additional phases play roles in the measurement of the CP phase δ_{cp} in the standard 3+0 scenario

The aim of this work is to study the consequences of the additional mass eigenstates and associated new degrees of freedom at LBL experiments specially at DUNE

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If nature has sterile neutrino(s), then how will it affect the CP violation as well as Mass Hierarchy measurements at DUNE

Neutrino Mixing

- N generation neutrino sector
- $\frac{N(N-1)}{2}$ mixing angles
- $\frac{(N-1)(N-2)}{2}$ phases (After rotating away $(2N-1)$ phases due to invariant Lagrangian under global phase transformation of the quark fields)

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In the $3+1$ model, the mixing matrix U^{3+1} is a 4×4 unitary matrix. It contains 6 mixing angles, and 3 oscillation-relevant CP-violating phases

3+1 Parameterization

- The 4×4 mixing matrix U^{3+1} can be written as:

$$U^{3+1}_{\text{PMNS}} = V(\theta_{34}, \delta_{34}) V(\theta_{24}, \delta_{24}) R(\theta_{14}) R(\theta_{23}) V(\theta_{13}, \delta_{13}) R(\theta_{12})$$

where, $V(\theta_{ij}, \delta_{ij})$ is a two dimensional rotation in the ij sector with an angle θ_{ij} and phase δ_{ij}.

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$$V(\theta_{24}, \delta_{24}) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_{24} & 0 & e^{-i\delta_{24}}\sin\theta_{24} \\ 0 & 0 & 1 & 0 \\ 0 & -e^{i\delta_{24}}\sin\theta_{24} & 0 & \cos\theta_{24} \end{pmatrix} \textit{etc.}$$

Constrains on Sterile Mixing Angles.

- $|U_{e4}|^2$ is constrained by the ν_e and $\bar{\nu}_e$ disappearance searches
- $|U_{\mu 4}|^2$ and $|U_{\tau 4}|^2$ are constrained by the ν_μ, $\bar{\nu}_\mu$ and NC disappearance searches
- $|U_{e4}|^2 \in [0, 0.1]$ which gives $\theta_{14} \in [0^\circ, 20^\circ]$ at 99% C.L.
- $|U_{\mu 4}|^2 \in [0, 0.03]$ gives $\theta_{24} \in [0^\circ, 11^\circ]$ at 99% C.L.
- $|U_{\tau 4}|^2 \in [0, 0.3]$ gives $\theta_{34} \in [0^\circ, 31^\circ]$ at 99% C.L.
- $\delta_{13} \in [-\pi, \pi]$, $\delta_{24} \in [-\pi, \pi]$, $\delta_{34} \in [-\pi, \pi]$

J. Kopp, P. A. N. Machado, M. Maltoni, and T. Schwetz, JHEP 1305, 050 (2013), 1303.3011

Full probability expression for vacuum in 3+1

$$
\begin{aligned}
P_{\mu e}^{4\nu} &= \frac{1}{2}\sin^2 2\theta_{\mu e}^{4\nu} \\
&+ (a^2\sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\sin^2 2\theta_{13}\sin^2 2\theta_{\mu e}^{4\nu})\left[\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right] \\
&+ \cos(\delta_{13}) b a^2 \sin 2\theta_{\mu e}^{3\nu}\left[\cos 2\theta_{12}\sin^2\Delta_{21} + \sin^2\Delta_{31} - \sin^2\Delta_{32}\right] \\
&+ \cos(\delta_{24}) b a \sin 2\theta_{\mu e}^{4\nu}\left[\cos 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21} - \sin^2\theta_{13}(\sin^2\Delta_{31} - \sin^2\Delta_{32})\right] \\
&+ \cos(\delta_{13}+\delta_{24}) a \sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\Big[-\frac{1}{2}\sin^2 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21} \\
&+ \cos 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})\Big] \\
&- \frac{1}{2}\sin(\delta_{13}) b a^2 \sin 2\theta_{\mu e}^{3\nu}\left[\sin 2\Delta_{21} - \sin 2\Delta_{31} + \sin 2\Delta_{32}\right] \\
&+ \frac{1}{2}\sin(\delta_{24}) b a \sin 2\theta_{\mu e}^{4\nu}\left[\cos^2\theta_{13}\sin 2\Delta_{21} + \sin^2\theta_{13}(\sin 2\Delta_{31} - \sin 2\Delta_{32})\right] \\
&+ \frac{1}{2}\sin(\delta_{13}+\delta_{24}) a \sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\left[\cos^2\theta_{12}\sin 2\Delta_{31} + \sin^2\theta_{12}\sin 2\Delta_{32}\right] \\
&+ (b^2 a^2 - \frac{1}{4}a^2\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{4\nu})\sin^2\Delta_{21}
\end{aligned}
$$

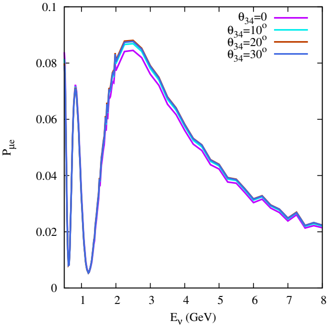
where,

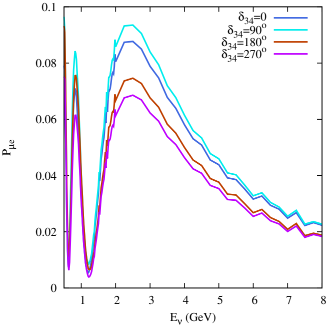
$$
\begin{aligned}
\sin 2\theta_{\mu e}^{3\nu} &= \sin 2\theta_{13}\sin\theta_{23} \\
b &= \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12} \\
\sin 2\theta_{\mu e}^{4\nu} &= \sin 2\theta_{14}\sin\theta_{24} \\
a &= \cos\theta_{14}\cos\theta_{24}
\end{aligned}
$$

Following observations can be made from the above probability expression:

- The vacuum appearance probability is independent of the 3-4 mixing angle and the associated CP phase
- Same conclusion can not be made for probability in matter
- Expression contain cosine and sin terms in δ_{24} and $(\delta_{13} + \delta_{24})$
- The terms involving the sine and cosine of the $(\delta_{13} + \delta_{24})$ can be significantly large and lead to appreciable changes in both the amplitude of the overall probability and the extent of CP violation

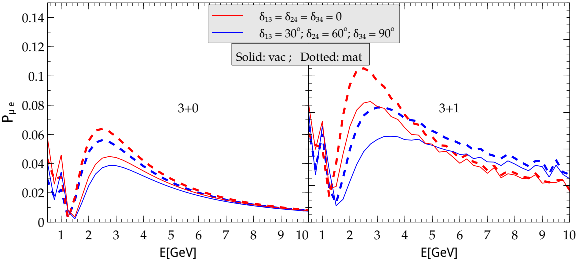
Dependency of $P_{\mu e}^{3+1}$ on θ_{34} and δ_{34} for matter





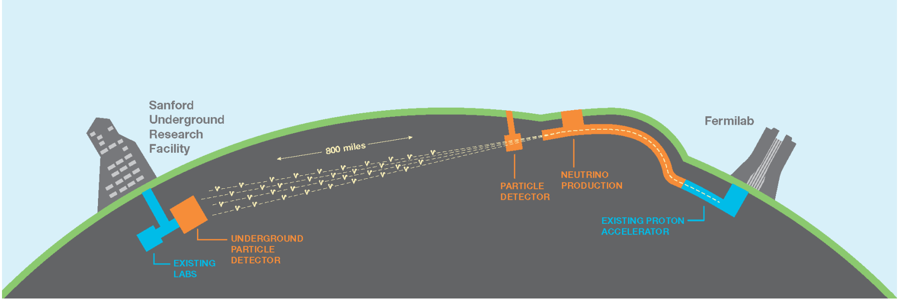
- In left fig, phases are 0 and $\theta_{14} = 20^\circ$, $\theta_{24} = 10^\circ$
- in right fig, $\delta_{13} = \delta_{24} = 0$, $\theta_{34} = 30^\circ$
- The parameters θ_{34}, δ_{34} are no longer inert in long baseline experiments where significant matter effect comes into play

Effect of sterile neutrino: Probability level



- Significant difference between blue solid and red solid curves in right panel when compared to the same in the left panel. This shows the effect of the additional CP phases. The difference gets more emphasized in presence of matter.
- Sterile parameters which are dormant at short baselines and in vacuum-like conditions are no longer inert in long baseline experiments
- Matter effect plays an important role

What is DUNE (Deep Underground Neutrino Experiment)?

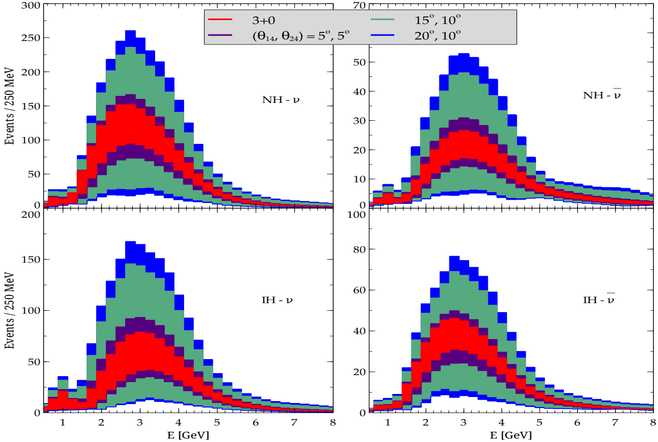


- A proposed long baseline experiment (the erstwhile LBNE)
- 1300 km baseline
- Underground Far detector possibly augmented with a near detector

Details of simulation for DUNE

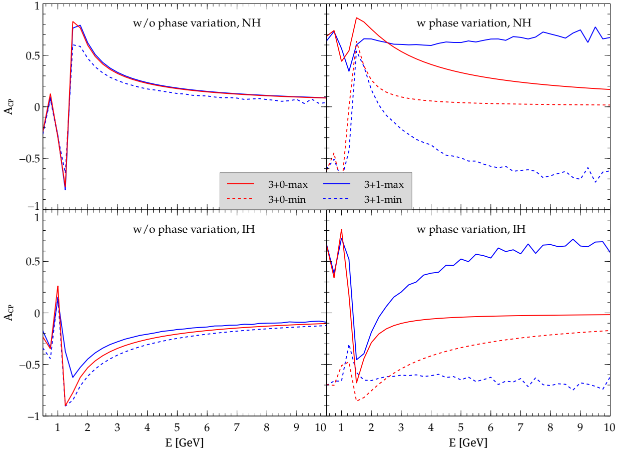
- 1.2 MW -120 GeV proton beam which delivers 10^{21} POT/yr.
- 35 kt liquid argon far detector at a baseline of 1300 km.
- 5 yrs. of ν + 5 yrs. of $\bar{\nu}$ running
- GLoBES was used to generate the results
- Averaging was done over the rapid oscillations induced by Δm^2_{41}

Effect of sterile neutrino: degeneracy in the event level



- 3+1 bands can potentially encompass the entire 3+0 band (red) leading to substantial degeneracy
- For sufficiently large mixing, a surfeit/ dearth of events are indicators to sterile states. But a highly capable ND is needed to draw such conclusions by making very precise flux measurements

Effect of sterile neutrino: spread in asymmetry



- $$A^{cp}_{\alpha\beta} = \frac{P(a \to b) - P(\bar{a} \to \bar{b})}{P(a \to b) + P(\bar{a} \to \bar{b})} = \frac{\Delta P_{\alpha\beta}}{P(a \to b) + P(\bar{a} \to \bar{b})}$$
- left panel:phases are zero and right panel: phases varied in $[-\pi : \pi]$. Additionally θ_{14}, θ_{24}, θ_{34}) were varied for both panels

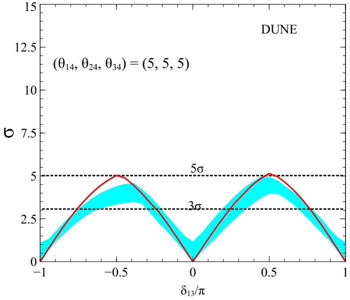
Sensitivity Measurements at DUNE and NOvA in 3+1 Scenario
The work is in progress.....
Just two slides....

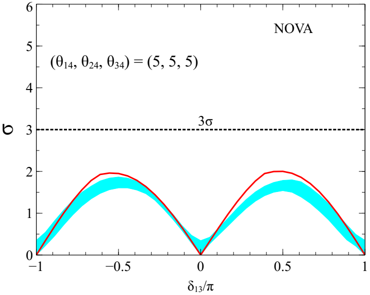
Details of simulation for NOvA

- Beam power of 0.7 MW, corresponding to 6×10^{20} protons on target per year
- 14 kton liquid scintillator far detector at a baseline of 810 km
- 3 years of ν + 3 years of $\bar{\nu}$

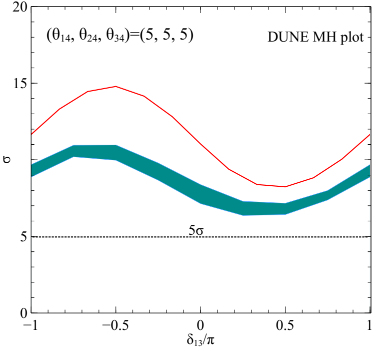
Sanjib Kumar Agarwalla, Suprabh Prakash, Sushant K. Raut, S. Uma Sankar, arXiv:1208.3644

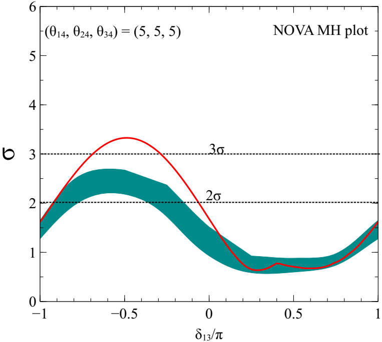
Sensitivity to measure CP violation





Sensitivity to measure mass hierarchy





- Presence of a sterile neutrino affects both CP and MH sensitivity at LBL experiments !!

Summary and conclusion

- Probability plots show that the effect of additional phases for sterile neutrino, coming from the interference term can be large. This is enhanced by the presence of matter, which brings in another phase into play.
- The interplay between additional phases results in significantly different spread of event rates. This effect increases with increasing mixing with the sterile sector.
- Thus sterile sector can potentially Obfuscate conclusive determinations of CP violation or conservation at FD. There is thus significant ambiguity as to whether any perceived CPV can be related to a unique phase (so called δ_{cp}) in 3+0 sector.
- This work emphasizes the need for a complementary SBL sterile-search program with a highly capable near detector so that DUNE may achieve its primary goal for CPV detection.


THANK
YOU